SIGNATURES FROM PHYSICS BEYOND THE STANDARD MODEL

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Abstract

A brief review is made of some of the experimental signatures that may be associated to a certain class of extensions of the standard model. The material of these lectures is divided into two sections.

After briefly sketching the present observational status of the neutrino masses I consider various schemes of neutrino mass generation, including those which are motivated by present experimental hints from solar and atmospheric neutrinos, as well as cosmological data on the amplitude of primordial density fluctuations.

Then some of the physics motivations and potential of various extensions of the standard model related to the electroweak breaking sector, such as supersymmetry, and extensions of the gauge boson sector are reviewed.

The new signatures associated with both types of extension may all be accessible to experiments performed either at accelerators or at underground installations. The complementarity between these two approaches in the search for signals beyond the standard model is most vividly manifest in the field of neutrino physics.

1 Introduction

Although extremely successful wherever it has been tested, our present standard $SU(2) \otimes U(1)$ model leaves open many of the fundamental issues of present-day particle physics. In the flavour sector, the most fundamental problems involve the understanding of what lies behind the mechanism of mass generation in general, as well as the properties of neutrinos.

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As is well known, the standard model relies on the Higgs mechanism which implies the existence of a fundamental scalar boson. If an elementary higgs boson exists it is widely believed that some stabilizing principle - e.g. supersymmetry (SUSY) - should be operative at the electroweak scale in order to explain the stability of its mass scale against quantum corrections associated with physics at superhigh energies. The observed joining of the three gauge coupling strengths as they are evolved from the presently accessible energies up to to a common scale of $\sim 10^{16}$ GeV provides circumstantial evidence that SUSY does indeed seem to set in somewhere at $M_{SUSY} \sim 10^3$ GeV. Unveiling the details of this rich structure constitutes one of the main goals in the agenda of the next generation of elementary particle colliders.

Another fundamental question mark in the standard model refers to the properties of neutrinos. Apart from being a theoretical puzzle, in the sense that there is no principle that dictates that neutrinos are massless, as postulated in the standard model, nonzero masses may in fact be required in order to account for a natural explanation of the data on solar and atmospheric neutrinos, as well as for the hot dark matter component of the universe. The implications of detecting nonzero neutrino masses could be very far reaching for the understanding of fundamental issues in particle physics, astrophysics, as well as the structure of our universe.

These two different types of extensions may be related in some models. As an example, I will consider the case of supersymmetric models with spontaneously broken R parity, which necessarily imply nonvanishing neutrino masses. I will describe how the extensions of the basic picture that seek to address the above two issues, such as higher unification and supersymmetry, may lead to extensions of the lepton and/or Higgs boson multiplet content, and thereby affect the physics of the electroweak sector in an important way. How to probe this physics both in accelerator as well as underground experiments will also be described.

2 Neutrino Mass

Neutrinos are the only apparently massless electrically neutral fermions in the standard model and the only ones without right-handed partners. It is rather mysterious that they seem to be so special when compared with the other fundamental fermions. Indeed, having no electric charge, a majorana mass term for neutrinos may arise even in the absence of right-handed components. However, many unified extensions of the standard model, such as SO(10), do require the presence of right-handed neutrinos in order to realize the extra symmetry. Either way one expects neutrinos to be massive. Moreover, there is, in these theories, a natural mechanism, called *seesaw*, to understand the relative smallness of neutrino masses [1, 2]. In general the seesaw mechanism provides just a general scheme, rather than detailed predictions. These will de-

pend, among other factors, upon the structure not only of the Dirac type entries, but also on the possible texture of the large Majorana mass term [3].

Although attractive, the seesaw mechanism is by no means the only way to generate neutrino masses. There are many other attractive possibilities, some of which do not require any new large mass scale. The extra particles required to generate the neutrino masses have masses at scales accessible to present experiments [4].

It is also quite plausible that B-L or lepton number, instead of being part of the gauge symmetry [5] may be a spontaneously broken global symmetry. The scale at which such a symmetry gets broken does not need to high, as in the original proposal [6], but can be rather low, close to the weak scale [7]. Such a low scale for lepton number breaking could have important implications not only in astrophysics and cosmology but also in particle physics.

This large diversity of possible schemes and the lack of a theory for the Yukawa couplings imply that present theory is not capable of predicting the scale of neutrino masses any better than it can fix the masses of the other fermions, like that of the muon. As a result one should at this point turn to experiment.

2.1 Limits

There are several limits on neutrino masses that follow from observation. The laboratory bounds may be summarized as [8]

$$m_{\nu_e} \lesssim 5\,\mathrm{eV}, \quad \mathrm{m}_{\nu_\mu} \lesssim 250\,\mathrm{keV}, \quad \mathrm{m}_{\nu_\tau} \lesssim 31\,\mathrm{MeV} \tag{1}$$

and follow purely from kinematics. These are the most model-independent of the neutrino mass limits. The improved limit on the ν_e mass from beta decays was recently given by Lobashev [9], while that on the ν_τ mass may be substantially improved at a future tau factory [10].

In addition, there are limits on neutrino masses that follow from the nonobservation of neutrino oscillations [11]. They involve neutrino mass differences versus mixing, and disappear in the limit of unmixed neutrinos. The present situation as well as future prospects to probe for neutrino oscillation parameters at long baseline experiments is given in Figure 1.

Another important limit arises from the non-observation of $\beta\beta_{0\nu}$ decay, i.e. the process by which nucleus $(A, Z-2)$ decays to $(A, Z) + 2\ e^-$. This lepton number violating process would arise from majorana neutrino exchange. In fact, as shown in ref. [12], a nonvanishing $\beta\beta_{0\nu}$ decay rate requires neutrinos to be majorana particles, irrespective of which mechanism induces it. This establishes a very deep connection which, in some special models, may be translated into a lower limit on the neutrino masses. The negative searches for $\beta\beta_{0\nu}$ in ^{76}Ge and

Figure 1: Oscillation parameters probed at present and future neutrino experiments

other nuclei leads to a limit of about one or two eV [14] on a weighted average neutrino mass parameter characterizing this process. Better sensitivity is expected from the upcoming enriched germanium experiments. Although rather stringent, this limit may allow relatively large neutrino masses, as there may be strong cancellations between the contributions of different neutrino types. This happens automatically in the case of a Dirac neutrino due to the lepton number symmetry [13].

In addition to laboratory limits, there is a cosmological bound that follows from avoiding the overabundance of relic neutrinos [15]

$$\sum_i m_{\nu_i} \lesssim 50\,\mathrm{eV} \tag{2}$$

This limit only holds if neutrinos are stable on cosmological time scales. There are many models where neutrinos decay into a lighter neutrino plus a majoron [2],

$$\nu_\tau \to \nu_\mu + J \ . \tag{3}$$

Lifetime estimates in various majoron models have been discussed in ref. [16]. These decays can be fast enough to obey the cosmological limits coming from the critical density requirement, as well as those that come from primordial big-bang nucleosynthesis [17]. Note also that, since these decays are *invisible*, they are consistent with all astrophysical observations. In view of the above it is worthwhile to continue in the efforts to improve present laboratory neutrino mass limits, including searches for distortions in the energy distribution of the electrons and muons coming from weak decays such as $\pi, K \to e\nu$, $\pi, K \to \mu\nu$, as well as kinks in nuclear β decays [18].

In addition to the above limits there are some positive *hints* for neutrino masses that follow from the following cosmological, astrophysical and laboratory observations.

2.2 Dark Matter

Recent observations of cosmic background temperature anisotropies on large scales by the COBE satellite [19], when combined with cluster-cluster correlation data e.g. from IRAS [20], indicate the need for the existence of a hot *dark matter* component, contributing about 30% to the total mass density [21]. A good fit is provided by a massive neutrino, for example, a tau neutrino in the few eV mass range. This suggests the possibility of having observable ν_e to ν_τ or ν_μ to ν_τ oscillations that may be accessible to the CHORUS and NOMAD experiments at CERN, as well as at the proposed P803 experiment at Fermilab [22]. This mass scale is also consistent with the recent preliminary hints in favour of neutrino oscillations recently reported by the LSND experiment [23].

2.3 Solar Neutrinos

The data collected up to now by Homestake and Kamiokande, as well as by the low-energy data on pp neutrinos from the GALLEX and SAGE experiments still pose a persisting puzzle [24, 25]. Comparing the data of GALLEX with the Kamiokande data indicates the need for a reduction of the ^{7} Be flux relative to the standard solar model expectation. Inclusion of the Homestake data only aggravates the discrepancy, suggesting that the solar neutrino problem is indeed a real problem. The allowed one sigma region for ^{7} Be and ^{8} Be fluxes is obtained as the intersection of the region to the left of line labelled 91 with the region labelled KAMIOKA in Figure 2. The lines are normalized with respect to the reference solar model of Bahcall and collaborators. Including the Homestake data of course only aggravates the discrepancy as can be seen from Figure 2.

Thus if one takes all data simultaneously one concludes that the simplest astrophysical solutions to the solar neutrino data are highly disfavored and that one needs new physics in the neutrino sector to account for the data [26]. The most attractive possibility is to assume the existence of neutrino conversions involving very small neutrino masses $\sim 10^{-3}$ eV [27]. The region of parameters allowed by present experiments is given in ref. [28]. Note that the fits favour the non-adiabatic over the large mixing solution, due mostly to the larger reduction of the ^{7} Be flux found in the former.

Figure 2: Allowed one sigma bands for ^{7} Be and ^{8} Be fluxes from all solar neutrino data

Figure 3: Region of solar neutrino oscillation parameters allowed by experiment

Figure 4: Region of atmospheric neutrino oscillation parameters from recent Kamiokande data.

2.4 Atmospheric Neutrinos

An apparent decrease in the expected flux of atmospheric ν_μ's relative to ν_e's arising from the decays of π's, K's and secondary muon decays produced in the atmosphere, has been observed in two underground experiments, Kamiokande and IMB, and possibly also at Soudan2 [29]. Although the predicted absolute fluxes of neutrinos produced by cosmic-ray interactions in the atmosphere are uncertain at the 20 % level, their ratios are expected to be accurate to within 5 %.

This atmospheric neutrino deficit can be ascribed to neutrino oscillations. Combining these experimental results with observations of upward going muons made by Kamiokande, IMB and Baksan, and with the negative Frejus and NUSEX results [30] leads to the following range of neutrino oscillation parameters

$$\Delta m^2_{\mu\tau} \approx 0.005 \; - \; 0.5 \text{ eV}^2, \; \sin^2 2\theta_{\mu\tau} \approx 0.5 \tag{4}$$

Recent results from Kamiokande on higher energy neutrinos strengthen the case for an atmospheric neutrino problem [31] as shown in Figure 4.

2.5 Models Reconciling Present Hints.

Can we reconcile the present hints from astrophysics and cosmology in the framework of a consistent elementary particle physics theory? The above observations suggest an interesting

theoretical puzzle whose possible resolutions will now be discussed.

2.5.1 Three Almost Degenerate Neutrinos

It is difficult to reconcile these three observations simultaneously in the framework of the simplest seesaw model with just the three known neutrinos . The only possibility to fit these observation in a world with just the three neutrinos of the standard model is if all of them have nearly the same mass ~ 2 eV [32].

It is known that the general seesaw models have two independent terms giving rise to the light neutrino masses. The first is an effective triplet vacuum expectation value [33] which is expected to be small in left-right symmetric models [5]. Based on this fact one can in fact construct extended seesaw models where the main contribution to the light neutrino masses (~ 2 eV) is universal, due to a suitable horizontal symmetry, while the splittings between ν_e and ν_μ explain the solar neutrino deficit and that between ν_μ and ν_τ explain the atmospheric neutrino anomaly [34].

2.5.2 Three Active plus One Sterile Neutrino

The alternative way to fit all the data is to add a fourth neutrino species which, from the LEP data on the invisible Z width, we know must be of the sterile type, call it ν_S . The first scheme of this type gives mass to only one of the three neutrinos at the tree level, keeping the other two massless [35]. In a seesaw scheme with broken lepton number, radiative corrections involving gauge boson exchanges will give small masses to the other two neutrinos ν_e and ν_μ [36]. However, since the singlet neutrino is superheavy in this case, there is no room to account for the three hints discussed above.

Two basic schemes have been suggested to keep the sterile neutrino light due to a special symmetry. In addition to the sterile neutrino ν_S , they invoke additional Higgs bosons beyond that of the standard model, in order to generate radiatively the scales required for the solar and atmospheric neutrino conversions. In these models the ν_S either lies at the dark matter scale [37] or, alternatively, at the solar neutrino scale [38]. In the first case the atmospheric neutrino puzzle is explained by ν_μ to ν_S oscillations, while in the second it is explained by ν_μ to ν_τ oscillations. Correspondingly, the deficit of solar neutrinos is explained in the first case by ν_e to ν_τ oscillations, while in the second it is explained by ν_e to ν_S oscillations. In both cases it is possible to fit all observations together. However, in the first case there is a clash with the bounds from big-bang nucleosynthesis. In the latter case the ν_S is at the MSW scale so that nucleosynthesis limits are satisfied. They single out the nonadiabatic solution uniquely. Note

however that, since the mixing angle characterizing the ν_μ to ν_τ oscillations is nearly maximal, the second solution is in apparent conflict with eq. (4) but agrees with Figure 4, taken from ref. [31]. Moreover, it can naturally fit the recent preliminary hints of neutrino oscillations of the LSND experiment [23].

Another theoretical possibility is that all active neutrinos are very light, while the sterile neutrino ν_S is the single neutrino responsible for the dark matter [39].

2.6 New Signatures in the Lepton Sector.

There are many motivations to extend the lepton sector of the electroweak theory. Extra heavy leptons may arise in models with a higher unification, for example those with left-right symmetry, SO(10) grand unified models, or superstrings. These models may contain isosinglet neutral heavy leptons and typically, also neutrino masses [2].

These isosinglet neutral heavy leptons (NHLS) may induce lepton flavour violating (LFV) decays such as $\mu \to e\gamma$, which are exactly forbidden in the standard model. Although these are a generic feature of models with massive neutrinos , in some cases, they may proceed in models where neutrinos are strictly massless [40, 41, 42].

In the simplest models of seesaw type [1] the NHLS are superheavy so that the expected rate for LFV processes is expected to be low, due to limits on neutrino masses. However, in other variants [40] this is not the case [42, 41] and this suppression need not be present. Indeed, present constraints on weak universality violation allow for decay branching ratios larger than the present experimental limits [43] so that these already are probing the masses and admixtures of the NHLS with considerable sensitivity. Similar estimates can be done for the corresponding tau decays [43, 44]. The results are summarized in Table 1. As an illustration, Figure 5 gives the expectations for the three charged lepton decays of the tau, taken from ref. [44]. Clearly these branching ratios lie within the sensitivities of the planned tau and B factories, as shown in ref. [45].

The physics of rare Z decays nicely complements what can be learned from the study of rare LFV muon and tau decays. The stringent limits on $\mu \to e\gamma$ preclude any possible detectability at LEP of the corresponding $Z \to e\mu$ decay. However the decays with tau number violation, $Z \to e\tau$ or $\mu\tau$ can be large. Similar statements can be made also for the CP violating Z decay asymmetries in these LFV processes [41]. Under realistic luminosity and experimental resolution assumptions, however, it is unlikely that one will be able to see these decays of the Z at LEP without a high luminosity option [46]. In any case, there have been dedicated experimental searches which have set good limits [47].

Figure 5: Expected branching ratios for $\tau \to 3e$ (solid) and $\tau \to \mu\mu e$

Table 1: Allowed τ decay branching ratios

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channel	strength
$\tau \to e\gamma, \mu\gamma$	$\lesssim 10^{-6}$
$\tau \to e\pi^0, \mu\pi^0$	$\lesssim 10^{-6}$
$\tau \to e\eta^0, \mu\eta^0$	$\lesssim 10^{-6} - 10^{-7}$
$\tau \to 3e, 3\mu, \mu\mu e, etc.$	$\lesssim 10^{-6} - 10^{-7}$

Figure 6: LEP sensitivities to $Z \to N\nu$ decays

If the NHLS are lighter than the Z, they may also be produced directly in Z decays such as † [48],

$$Z \to N_\tau + \nu_\tau \tag{5}$$

Note that the isosinglet neutral heavy lepton N_τ is singly produced, through the off-diagonal neutral currents characteristic of models containing doublet and singlet leptons [33]. Subsequent N_τ decays would then give rise to large missing energy events, called zen-events. Expectations for the attainable rates for such processes are illustrated in Figure 6, taken from ref. [48] One sees that this branching ratio can be as large as $\lesssim 10^{-3}$ a value that is already superseded by the good limits on such decays from the searches for acoplanar jets and lepton pairs from Z decays at LEP, although some inconclusive hints have been recently reported by ALEPH [47]

Finally we note that there can also be large rates for lepton flavour violating decays in models with radiative mass generation [4]. For example, this is the case in the models proposed to reconcile present hints for neutrino masses [37]. The expected decay rates may easily lie within the present experimental sensitivities and the situation should improve at PSI or at the proposed tau-charm factories.

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†There may also be CP violation in lepton sector, even when the known neutrinos are strictly massless and lead to Z decay asymmetries $\mathcal{O}\ (10^{-7})$ [41]

Table 2: Allowed branching ratios for rare Z decays.

channel	strength
$Z \to N_\tau\ \nu_\tau$	$\lesssim 10^{-3}$
$Z \to e\tau$	$\lesssim 10^{-6} - 10^{-7}$
$Z \to \mu\tau$	$\lesssim 10^{-7}$

2.7 Outlook

Besides being suggested by theory, neutrino masses seem to be required to fit present astrophysical and cosmological observations, in addition to the recent LSND hints [23].

Neutrinos could be responsible for a wide variety of measurable implications at the laboratory. These new phenomena would cover an impressive range of energies, starting with β and nuclear $\beta\beta_{0\nu}$ decays. Searches for the latter with enriched germanium could test the quasidegenerate neutrino scenario for the joint explanation of hot dark matter and solar and atmospheric neutrino anomalies. Moving to neutrino oscillations, here one expects much larger regions of oscillation parameters in the ν_e to ν_τ and ν_μ to ν_τ channels will be be probed by the accelerator experiments at CERN than now possible with present accelerators and reactors. On the other hand more data from low energy pp neutrinos as well as from Superkamiokande, Borexino, and Sudbury will shed light on the solar neutrino issue. Fortunately these experiments are expected to run in the next couple of years or so.

For the far future we look forward to the possibility of probing those regions of ν_μ to ν_e or ν_S oscillation parameters suggested by present atmospheric neutrino data. This will be possible at the next generation of long baseline experiments. Similarly, a new generation of experiments capable of more accurately measuring the cosmological temperature anisotropies at smaller angular scales than COBE, would test different models of structure formation, and presumably shed further light on the need for hot neutrino dark matter.

Neutrinos may also imply rare processes with lepton flavour violation, as well as new signatures at LEP energies and even higher, whose allowed rates have been summarized in Tables 1 and 2. Such experiments are complementary to those at low energies and can also indirectly test neutrino properties in an important way.

3 Electroweak Symmetry Breaking

A lot of research effort has been recently devoted to the physics associated to the electroweak breaking sector and its possible manifestations at present and future particle colliders. If indeed the higgs boson exists as an elementary particle, the forerunner in these investigations is the study of supersymmetric extensions of the standard model and its corresponding experimental searches at high energy accelerators.

The prototype of these models is called the minimal supersymmetric standard model (MSSM) [49]. This model realizes SUSY in the presence of a discrete R parity (R_p) symmetry, postulated *ad hoc*. Under this symmetry all standard model particles are even while their partners are odd. As a result of this selection rule, in the so-called minimal supersymmetric standard model SUSY particles are only produced in pairs, with the lightest of them (LSP) being stable. It has been suggested as a candidate for the cold dark matter of the universe and several methods of detection at underground installations have been suggested [50].

So far all searches for supersymmetric particles have been negative. However, presently accessible energies cover only a small part of the parameter space of supersymmetric theories. One may summarize the present situation as follows. The electrically charged weakly interacting SUSY states, sleptons, charginos as well as SUSY higgs bosons have bounds close to the available beam energy at LEP. There is only a small room for improvement left at LEP1 on the masses of the electrically neutral SUSY particles. As for the strongly interacting SUSY states, gluinos and squarks, their mass bounds come form the Tevatron and there is little room for improvement with the present setup.

Thus it seems that one has to wait for the new generation of particle colliders, LEP2 and the LHC in order to improve the search potential for supersymmetric models. Indeed, this topic forms one of the important goals in the agenda of these elementary particle colliders.

As will be shown in the next section, one has not yet reached the border of what can be reached with present installations in the searches for SUSY particles if one abandons the assumption that R parity is conserved. Indeed one can have genuine SUSY signals that can be searched for even at LEP1 with the required sensitivity to make the searches meaningful.

3.1 Supersymmetry.

Unfortunately there is no clue as to how SUSY is realized. Nobody knows the origin of the R parity symmetry and whether it is indeed a necessary requirement to impose on supersymmetric extensions of the standard model. Therefore there is no firm theoretical basis for the most

Figure 7: Allowed branching ratios for $Z \to \chi^{\pm}\tau^{\mp}$

popular *ansatz*, the minimal supersymmetric standard model (MSSM). It is indeed of great interest to investigate theories without R parity [2].

There are many ways to break it, either explicitly or spontaneously (RPSUSY models). Here we focus on the case of spontaneous R_p breaking in the $SU(2) \otimes U(1)$ theory. The viability of this possibility has been recently demonstrated. The breaking of R-parity is driven by right-handed *isosinglet* sneutrino vacuum expectation values (VEVS) [52], so that the associated Goldstone boson (majoron) is mostly singlet and as a result the Z does not decay by majoron emission, in agreement with LEP observations [51].

If R parity is broken spontaneously it shows up primarily in the couplings of the W and the Z, leading to rare Z decays such as the single production of the charginos and neutralinos [53], for example,

$$Z \to \chi^{\pm}\tau^{\mp} \tag{6}$$

where the lightest chargino mass is assumed to be smaller than the Z mass. In the simplest models, the magnitude of R parity violation is correlated with the nonzero value of the ν_τ mass and is restricted by a variety of experiments. Nevertheless the R parity violating Z decay branching ratios, as an example, can easily exceed 10^{-5}, well within present LEP sensitivities. This is illustrated in Figure 7. Similarly, the lightest neutralino (LSP) could also be singly-produced as [53]

$$Z \to \chi^0\nu_\tau \tag{7}$$

Being unstable due to R parity violation, χ^0 is not necessarily an origin of events with missing

energy, since some of its decays are into charged particles. Thus the decay $Z \to \chi^0 \nu_\tau$ would give rise to zen events, similar to those of the MSSM but where the missing energy is carried by the ν_τ . Another possibility for zen events in RPSUSY is the usual pair neutralino production process, where one χ^0 decays visibly and the other invisibly. The corresponding zen-event rates can be larger than in the MSSM.

Although the ν_τ can be quite massive in these models, it is perfectly consistent with cosmology [15] including primordial nucleosynthesis [17], since it decays sufficiently fast by majoron emission [16]. On the other hand, the ν_e and ν_μ have a tiny mass difference in the model of ref. [52]. This mass difference can be chosen to lie in the range where resonant ν_e to ν_μ conversions provides an explanation of solar neutrino deficit [27]. Due to this peculiar hierarchical pattern, one can go even further, and regard the rare R parity violating processes as a tool to probe the physics underlying the solar neutrino conversions in this model [54]. Indeed, the rates for such rare decays can be used in order to discriminate between large and small mixing angle MSW solutions to the solar neutrino problem [27]. Typically, in the nonadiabatic region of small mixing one can have larger rare decay branching ratios, as seen in Figure 5 of ref. [54].

It is also possible to find manifestations of R parity violation at the superhigh energies available at hadron supercolliders such as LHC. Either SUSY particles, such as gluinos, are pair produced and in their cascade decays the LSP decays or, alternatively, one violates R parity by singly producing the SUSY states. An example of this situation has been discussed in ref. [55]. In this reference one has studied the single production of weakly interacting supersymmetric fermions (charginos and neutralinos) via the Drell Yan mechanism, leading to possibly detectable signatures. More work on this will be desirable.

Another possible signal of the RPSUSY models based on the simplest $SU(2) \otimes U(1)$ gauge group is rare decays of muons and taus. In this model the spontaneous violation of R parity generates a physical Goldstone boson, called majoron. Its existence is quite consistent with the measurements of the invisible Z decay width at LEP, as it is a singlet under the $SU(2) \otimes U(1)$ gauge symmetry. In this model the lepton number is broken close to the weak scale and can produce a new class of lepton flavour violating decays, such as those with single majoron emission in μ and τ decays. These would be "seen" as bumps in the final lepton energy spectrum, at half of the parent lepton mass in its rest frame. The allowed rates for single majoron emitting μ and τ decays have been determined in ref. [56] and are also shown in table 3 to be compatible with present experimental sensitivities [8]. As an illustration, I borrow Figure 8 from ref. [56]. This example also illustrates how the search for rare decays can be a more sensitive probe of neutrino properties than the more direct searches for neutrino masses, and therefore complementary. Moreover, they are ideally studied at a tau-charm factory [45].

Table 3: Allowed branching ratios for rare decays in the RPSUSY model. χ denotes the lightest electrically charged SUSY fermion (chargino) and χ^0 is the lightest neutralino.

channel	strength
$Z \to \chi\tau$	$\lesssim 6 \times 10^{-5}$
$Z \to \chi^0 \nu_\tau$	$\lesssim 10^{-4}$
$\tau \to \mu + J$	$\lesssim 10^{-3}$
$\tau \to e + J$	$\lesssim 10^{-4}$

Figure 8: Allowed branching ratios for $\tau \to e + J$ versus m_{ν_τ}

3.2 Higgs Bosons.

Another possible, albeit quite indirect, manifestation of the properties of neutrinos and the lepton sector is in the electroweak breaking sector. Many extensions of the lepton sector seek to give masses to neutrinos through the spontaneous violation of an ungauged U(1) lepton number symmetry, thus implying the existence of a physical Goldstone boson, called majoron [6]. As already mentioned above this is consistent with the measurements of the invisible Z decay width at LEP if the majoron is (mostly) a singlet under the $SU(2) \otimes U(1)$ gauge symmetry.

Although the original majoron proposal was made in the framework of the minimal seesaw model, and required the introduction of a relatively high energy scale associated to the mass of the right-handed neutrinos [6], there are many attractive theoretical alternatives where lepton number is violated spontaneously at the weak scale or lower. In this case although the majoron has very tiny couplings to matter and the gauge bosons, it can have significant couplings to the Higgs bosons. As a result one has the possibility that the Higgs boson may decay with a substantial branching ratio into the invisible mode [7]

$$h \to J \ + \ J \tag{8}$$

where J denotes the majoron. The presence of this invisible decay channel can affect the corresponding Higgs mass bounds in an important way.

The production and subsequent decay of a Higgs boson which may decay visibly or invisibly involves three independent parameters: its mass M_H, its coupling strength to the Z, normalized by that of the standard model, ϵ^2, and its invisible decay branching ratio. The LEP searches for various exotic channels can be used in order to determine the regions in parameter space that are already ruled out, as described in ref. [57]. The exclusion contour in the plane ϵ^2 vs. M_H, was shown in Figure 9 taken from ref. [58].

Another mode of production of invisibly decaying Higgs bosons is that in which a CP even Higgs boson is produced at LEP in association with a massive CP odd scalar [59]. This production mode is present in all but the simplest majoron model containing just one complex scalar singlet in addition to the standard model Higgs doublet. Present limits on the relevant parameters are given in Figure 10, taken from ref. [59]. In this plot we have assumed BR $(H \to J \, J) = 100\%$ and a visibly decaying A boson.

Finally, the invisible decay of the Higgs boson may also affect the strategies for searches at higher energies. For example, the ranges of parameters that can be covered by LEP2 searches for a total integrated luminosity of 500 pb^{-1} and various centre-of-mass energies have been given in Figure 9. Similar analysis were made for the case of a high energy linear e^+e^- collider (NLC) [60], as well as for the LHC [61].

Figure 9: Region in the ϵ^2 vs. m_H that can be excluded by the present LEP1 analyses (solid curve). Also shown are the LEP2 extrapolations (dashed).

Figure 10: Limits on ϵ_A^2 in the m_A, m_H plane that can be placed by present LEP1 searches based on the $e^+e^- \to H\ A \to J\ Jb\bar{b}$ production channel.

Figure 11: Limits on Z' bosons in constrained string type models based on E_6

3.3 New Gauge Bosons.

Superstring extensions of the standard model suggest the existence of additional gauge bosons at the TeV scale and this may affect the lepton sector and the interactions of neutrinos. Although there are other possibilities, we focus here on models based on an underlying E_6 symmetry [2].

The fantastic agreement found between the standard model predictions and the experimental measurements from the scale of the atom to that probed at LEP places stringent restrictions on the existence of an additional Z' at low energies [62]. Indeed, if such boson were sufficiently light and mixed with the usual Z it would modify the couplings of leptons to the Z and be thereby restricted by low energy neutral current data, as well as by the LEP precision data on Z decays [62]. In string models the Higgs sector is constrained in such a way that these limits are strongly correlated with the top quark mass [63]. This is illustrated in Figure 11, taken from ref. [63]. One sees that the recent data from the CDF collaboration leads to constraints around a TeV on the Z' mass for such string type models based on the E_6 gauge group. The limits are much weaker in the case of unconstrained models.

3.4 Outlook

There is a wealth of related phenomena covering a broad range of energies and of experimental situations that may probe the physics underlying the extensions we have discussed here. They involve signatures in the neutrino sector, such as oscillations, neutrinoless double beta decays

and possible distortions in beta decay spectra. A large number of related processes can also manifest themselves at muon and tau factories and at high energy e^+e^- collisions (e.g. LEP and NLC). These have been summarized in Table 3. There are also good prospects to observe some of these signatures at the upcoming hadron supercolliders LHC. Examples of these processes range from μ and τ number violating decays, up the high energy processes associated with the single production of SUSY fermions or neutral heavy leptons (NHLS) at LEP or at a future hadron supercollider. Finally let me highlight in this context the rather peculiar possibility that the Higgs boson may decay dominantly by two majoron emission, leading to missing momentum events. As we saw, new search strategies are required to cover this possibility. All of the above effects related to nonstandard neutrino properties may be accessible to experiment.

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